Accelerator Considerations and the APS Upgrade

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Outline

- Review of beam parameters
- Expected variation in parameters
- APS-U lattice possibilities

Description of Beam Distribution

- Electron beam is described by distribution in 6d trace space
  - Horizontal and vertical coordinates: $x=x_1$ and $y=x_3$
  - Horizontal and vertical slopes: $x'=x_2$ and $y'=x_4$
  - Time and momentum deviation: $\Delta t=x_5$ and $\delta=x_6$
- Gaussian distribution in all coordinates
  - Significant deviations occur only in time distribution (more later)
- Beam can be described by the 6d "sigma matrix"

$$\Sigma_{ij} = \langle x_i x_j \rangle$$

where angle brackets mean averaging over all electrons in a bunch.

Special Cases

In a well-corrected machine, we have a nearly uncoupled matrix

$$\Sigma = \begin{bmatrix} \Sigma_x & 0 & \begin{matrix} 0 & \Sigma_{16} \\ 0 & \Sigma_{26} \end{matrix} \\ 0 & \Sigma_y & \begin{matrix} 0 & \Sigma_{36} \\ 0 & \Sigma_{46} \end{matrix} \\ 0 & 0 & \Sigma_z \end{bmatrix}$$

Beam without x-y tilt.

"Never" strictly correct in a real storage ring because of inevitable magnet strength and alignment errors.

At symmetry points, we have a "waist" or "upright ellipse," e.g.,

$$\Sigma_x = \begin{bmatrix} \sigma_x^2 & 0 \\ 0 & \sigma_{x'}^2 \end{bmatrix}$$

Brightness calculations presently assume this description is correct at center of ID.

Relationship to “Lattice Functions”

$$\Sigma_x = \begin{bmatrix} \epsilon_x \beta_x + (\eta_x \sigma_\delta)^2 & -\alpha \epsilon_x + \sigma_\delta^2 \eta_x \eta_x' \\ -\alpha \epsilon_x + \sigma_\delta^2 \eta_x \eta_x' & \epsilon_x \frac{1+\alpha_x^2}{\beta_x} + (\eta_x' \sigma_\delta)^2 \end{bmatrix}$$

$\beta_x \ldots$	Envelope or Beta functions
$\alpha_x = -\frac{1}{2}\frac{\partial \beta_x}{\partial s} \ldots$	Zero at symmetry point
$\eta_x \ldots$	Dispersion function
$\eta_x' = \frac{\partial \eta_x}{\partial s} \ldots$	Zero at symmetry point
$\epsilon_x \ldots$	Emittance
σ_δ	Fractional momentum spread

Relationship to Lattice Functions

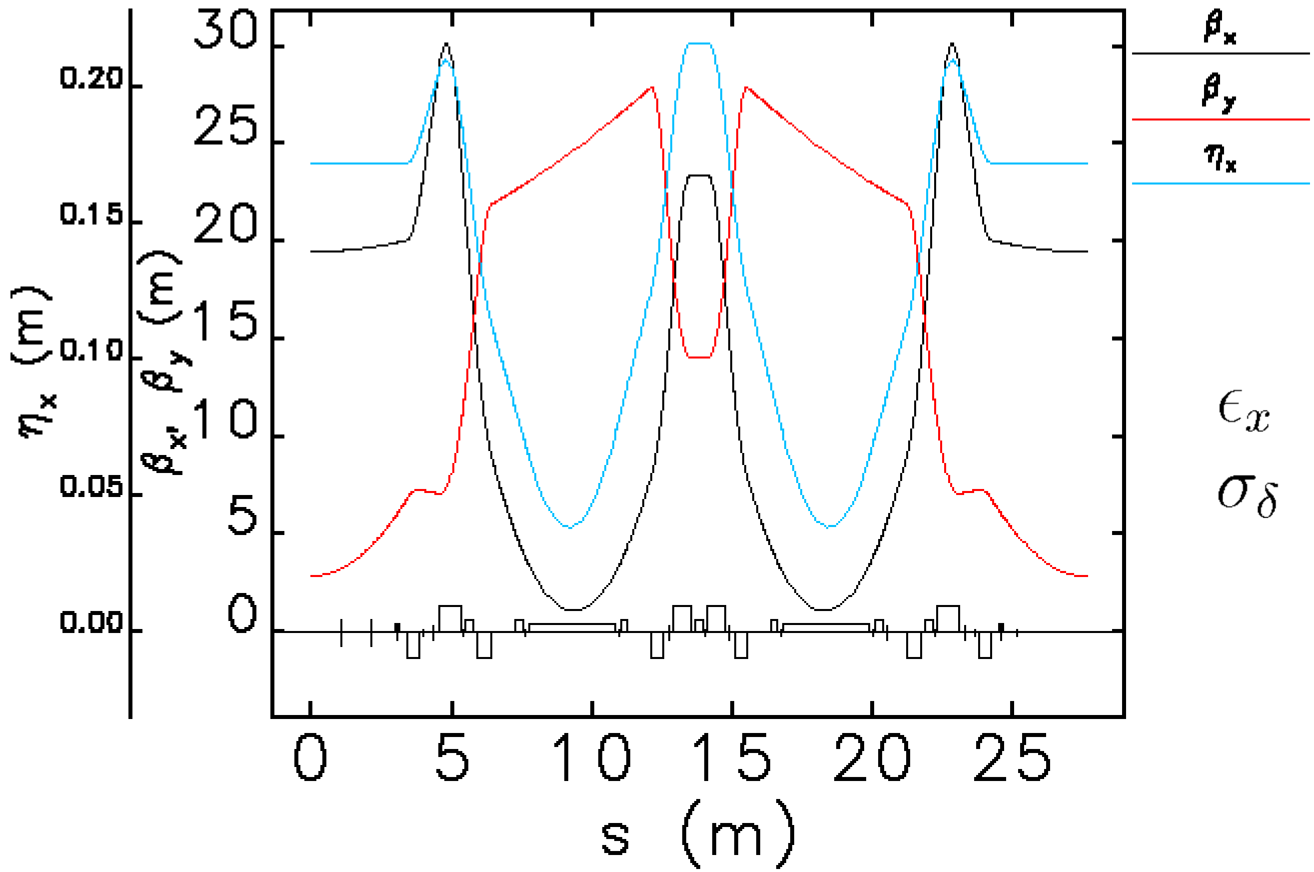
$$\Sigma_x = \begin{bmatrix} \epsilon_x \beta_x + (\eta_x \sigma_\delta)^2 & 0 \\ 0 & \frac{\epsilon_x}{\beta_x} \end{bmatrix}$$

Valid at symmetry points.

Effective emittance is related to determinant of sigma matrix

$$\epsilon_{x,eff} = \sqrt{\det \Sigma_x} = \epsilon_x \sqrt{1 + \frac{(\eta_x \sigma_\delta)^2}{\epsilon_x \beta_x}}$$

Nominal APS Lattice Functions



$$\epsilon_x = 2.51nm$$
$$\sigma_\delta = 0.0955\%$$

Lattice Functions and Electron Dynamics

- Lattice functions have meaning for individual particle dynamics

$$x_i(s) = \underbrace{\sqrt{2J_i\beta_x}\cos\phi_{i,x}(s)}_{\substack{\text{betatron}\\ \text{oscillation}}} + \underbrace{\delta_i\eta_x(s)}_{\substack{\text{dispersive}\\ \text{orbit}}} + \underbrace{x_{co}(s)}_{\substack{\text{closed}\\ \text{orbit}}}$$

- Emittance is just the average action

$$\epsilon_x = \langle J_i \rangle$$

- The energy offset δ_i also varies but frequency is an order of magnitude less than for betatron oscillations

Determination of Emittance and Energy Spread

- Emittance and energy spread are non-zero because of quantum excitation of actions and energy deviations
  - Electrons emit synchrotron radiation in magnetic fields (dipoles, quadrupoles, IDs, etc.)
  - For APS, radiation is mostly emitted in dipoles
    - 5.4 MeV/turn
    - About 140 photons per electron per turn
    - Energy and number of photons emitted is random ➔ energy spread
    - Location of emission is random and dispersive ➔ emittance
    - Damping of excitation occurs due to reacceleration

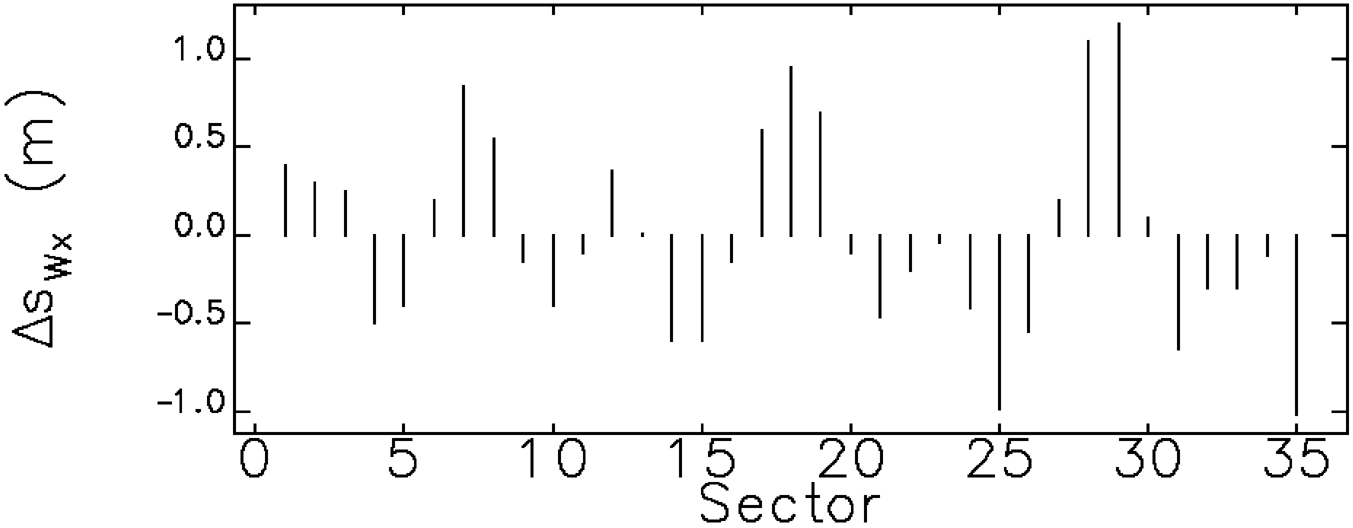
$$\Sigma = R^T \Sigma R + D$$

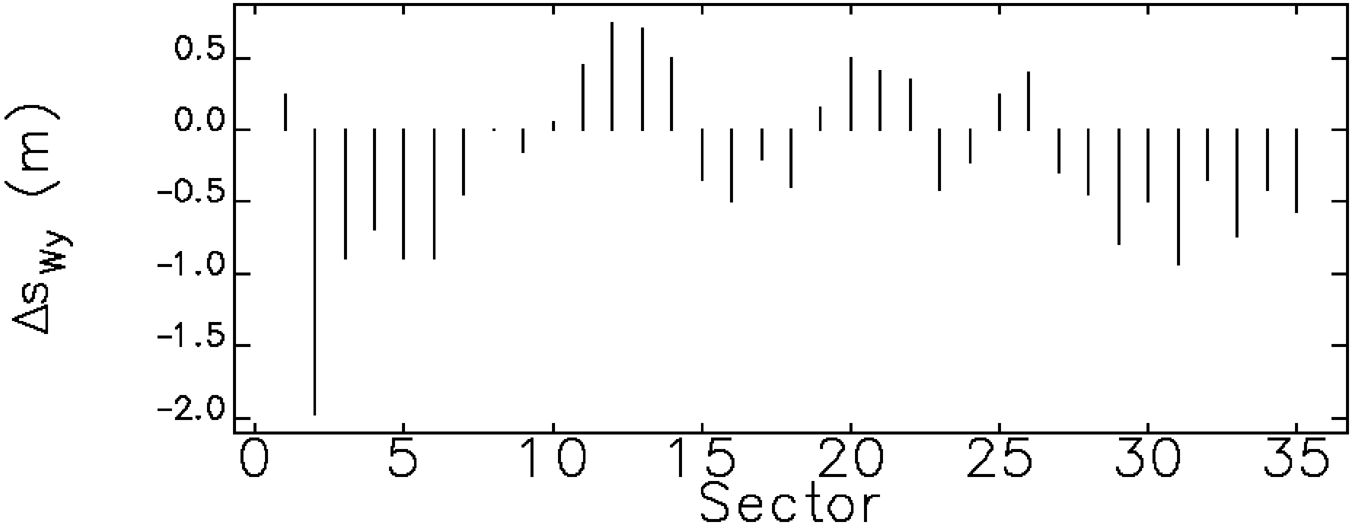
  - We can reduce these effects by
    - Stronger focusing, could get ~15% reduction
    - Quadrupole transverse offsets, could get 2-fold emittance reduction
  - These approaches would be difficult to incorporate into the upgrade

Deviations from Simplified Cases

- Lattice function errors
  - These are generally small, at the 1~2% level
  - May become larger globally after significant steering for a beamline
  - We hope to eventually provide up-to-date predictions of this during a run
- Coupling of x and y planes
  - Coupling results in tilted beams and waist offsets
  - Sources of coupling
    - Magnet roll
    - Beamline steering in vertical plane
    - Use of skew quads to increase lifetime
  - Beamline steering is a major contributor and will be phased out
  - We hope to improve coupling control as part of the upgrade

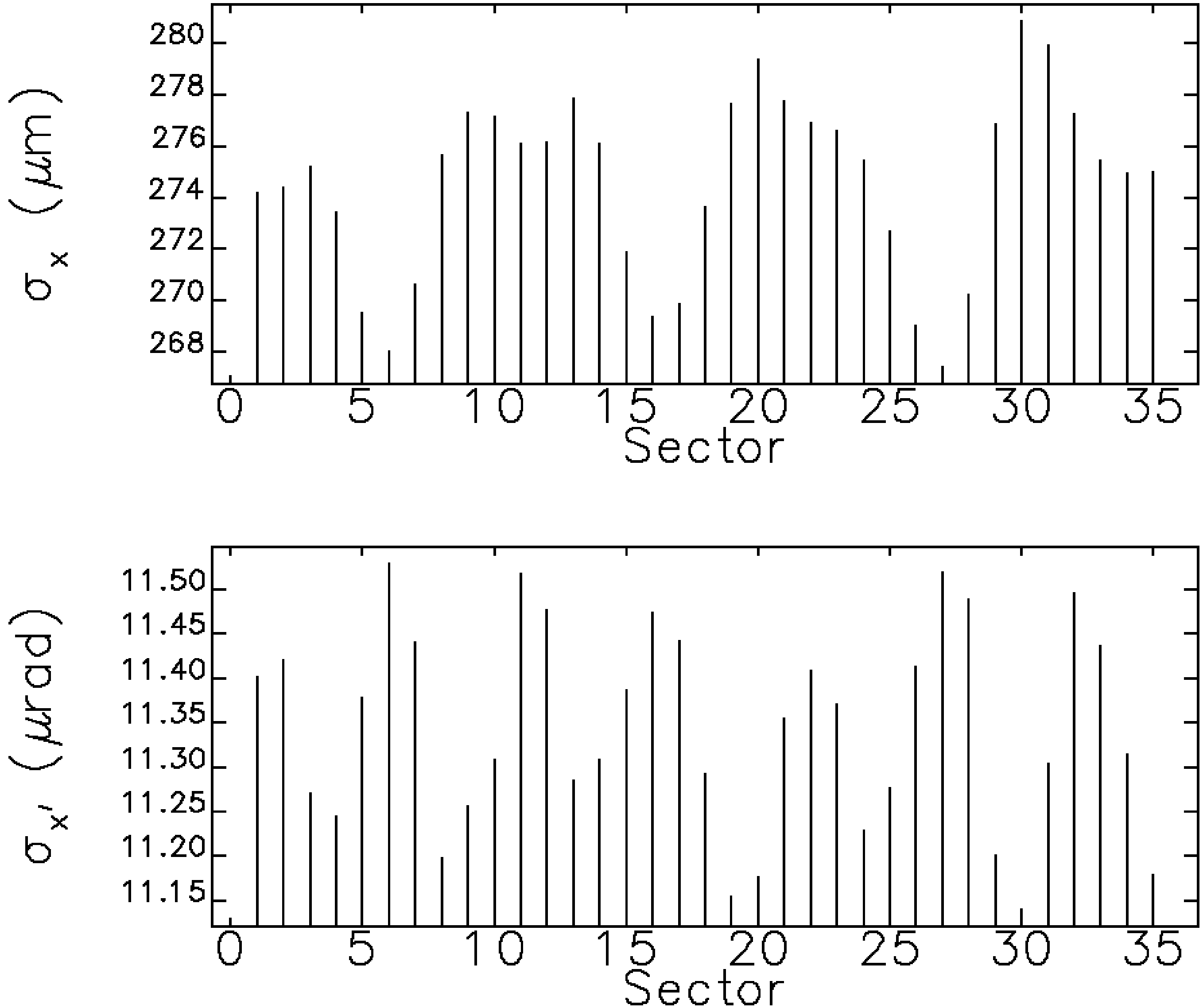
Waist Offsets from Center of Straight (Example)





Calibrated lattice model provided by V. Sajaev.

Beam Sizes and Divergences at Waists (Example)



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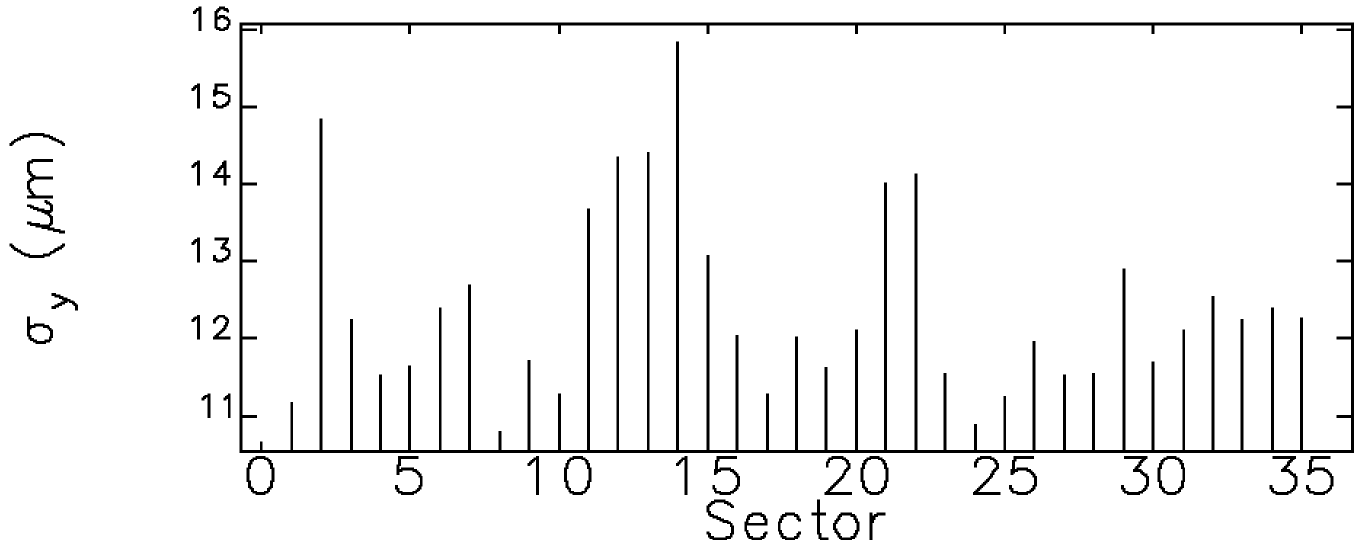

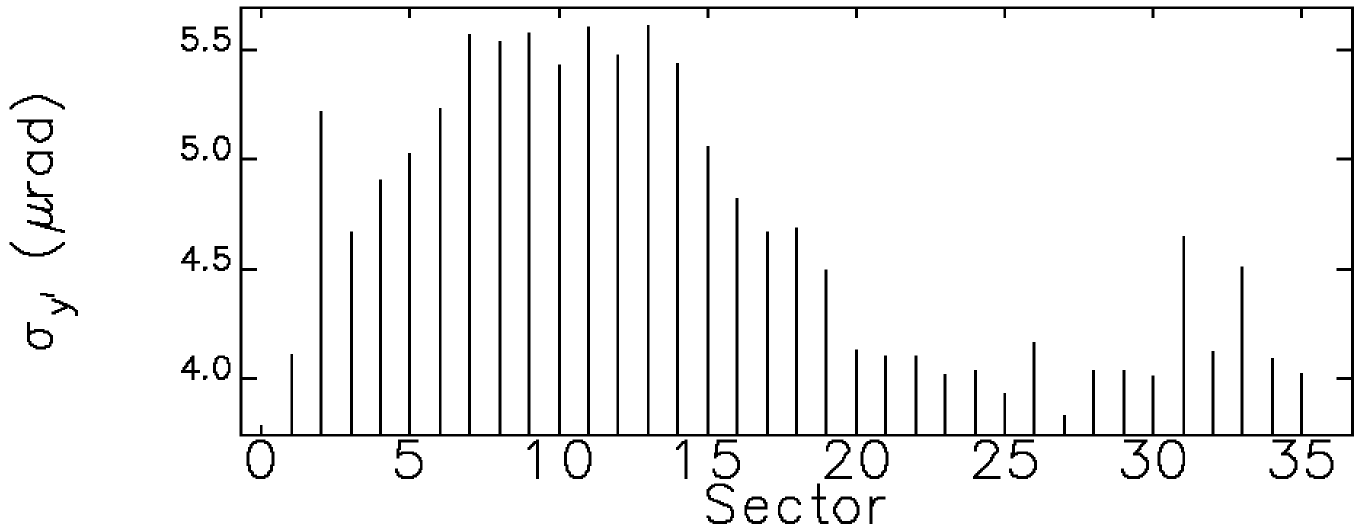

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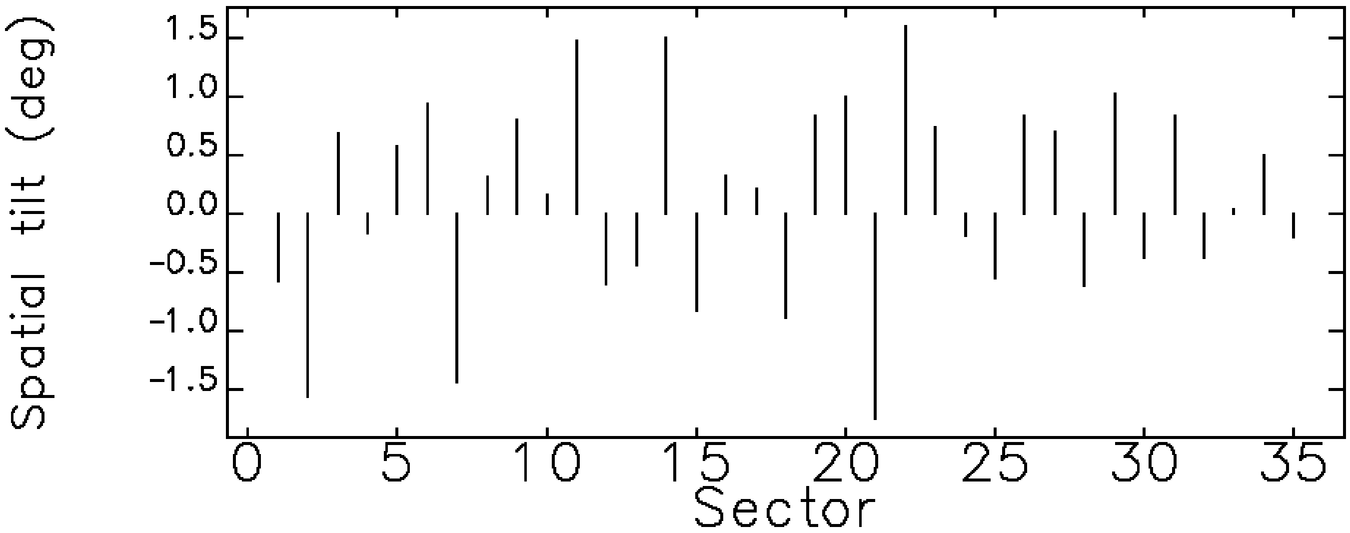
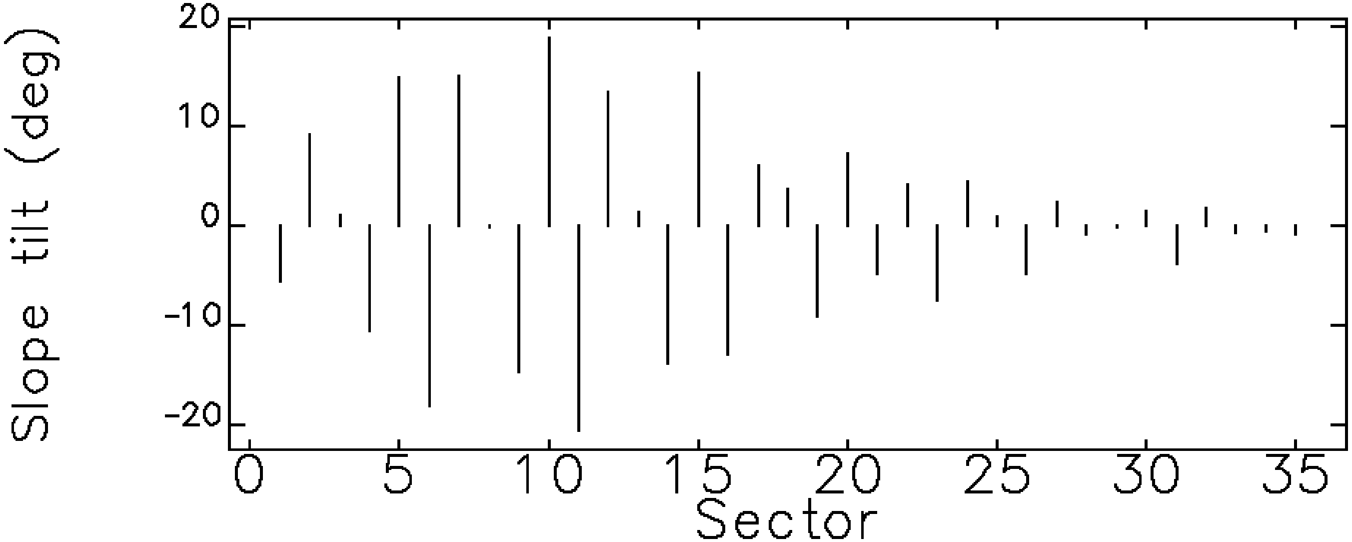
Tilts in Electron Beam at Vertical Waist (Example)





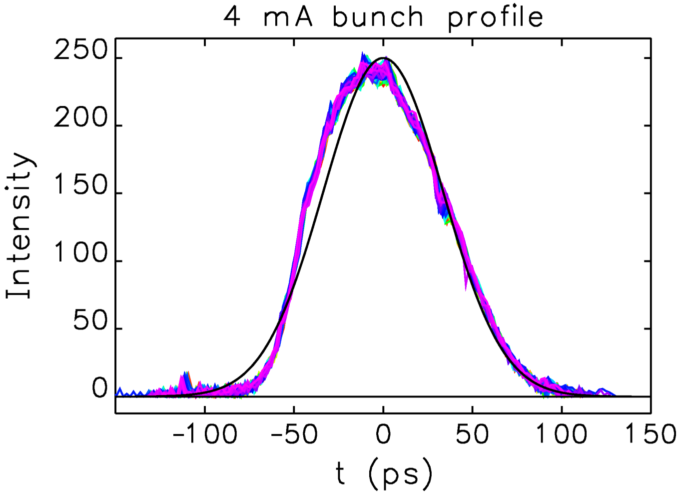
Calibrated lattice model provided by V. Sajaev.

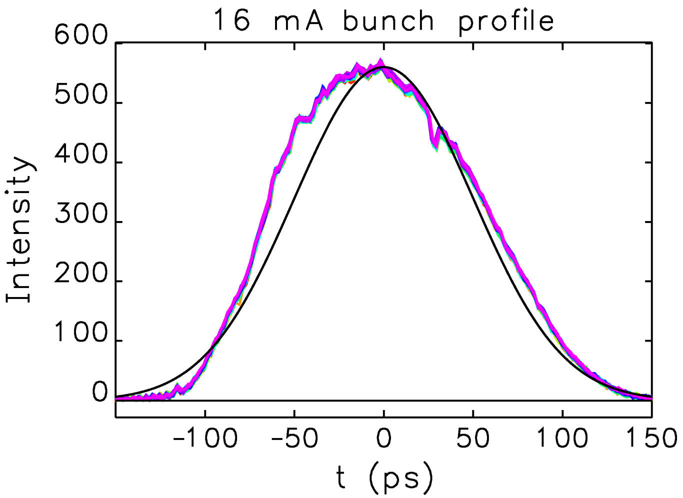
Time/Energy Distribution

- Bunch duration varies with bunch current

$$\sigma_t(ps) = 25.1 I_b[mA]^{0.1484+0.0346 \log_e I_b}$$

- Only gaussian in limit of zero current





Graphs courtesy V. Sajaev.

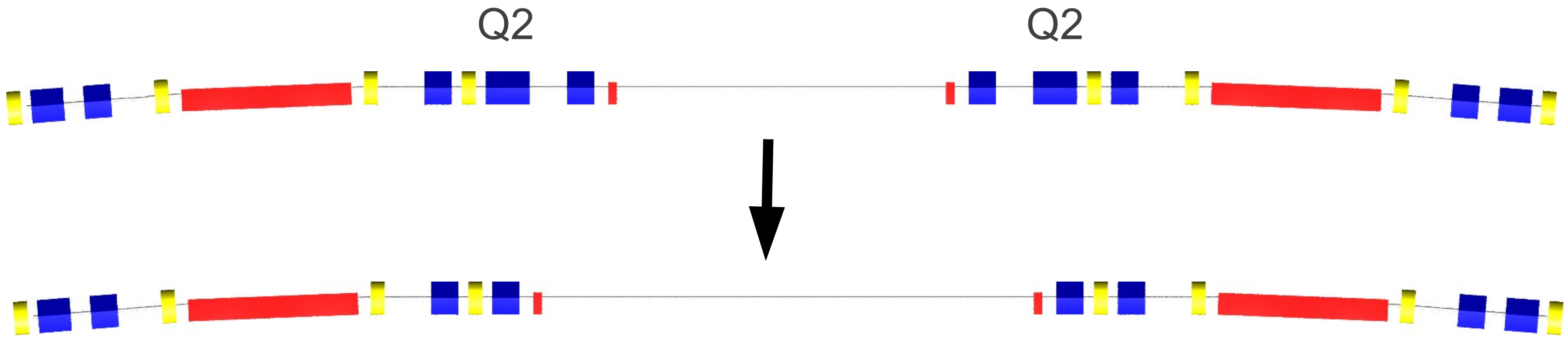
- Energy distribution is gaussian
  - 0.0955% spread up to about 7 mA
  - Grows ~linearly above that, ~1.2% at 16mA (Y. Chae *et al.*, Proc. PAC07, FRPMN104).

Upgrade Lattice

- Primary change for upgrade will be several long straight sections (LSSs)
- Reduction in emittance considered less important
- Also need to accommodate electron optics requirements of short-pulse x-ray (SPX) system
  - Requires LSS+SSS+LSS sequence
  - Requires specific betatron phase advance
- Have one request for an RHB insertion

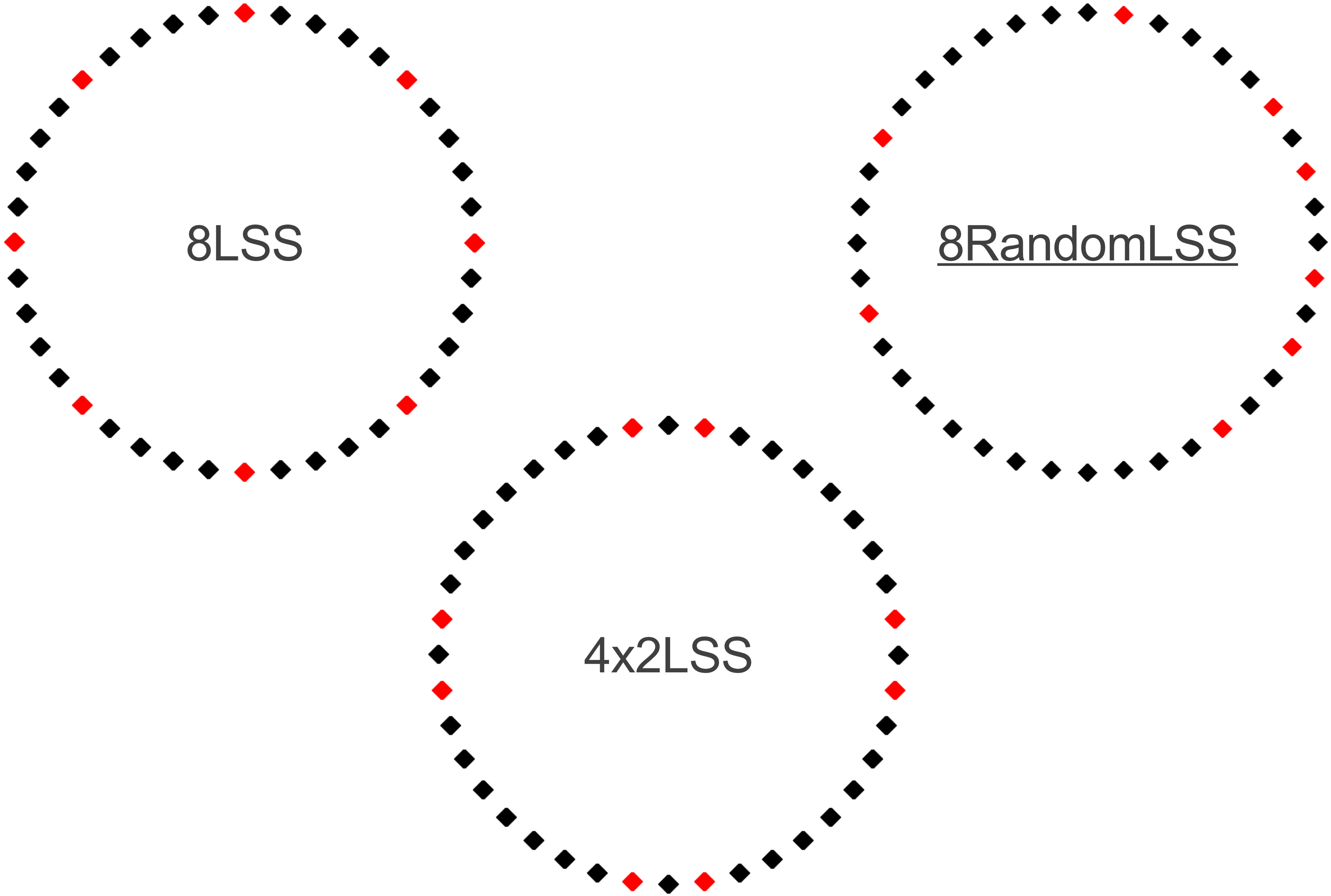
LSS scheme

- LSS can be implemented at APS with a simple scheme
  - Remove the Q2 magnets on either side of SS
  - Remove the adjacent correctors
  - Remove the adjacent BPMs
  - Slide other components away from the ID



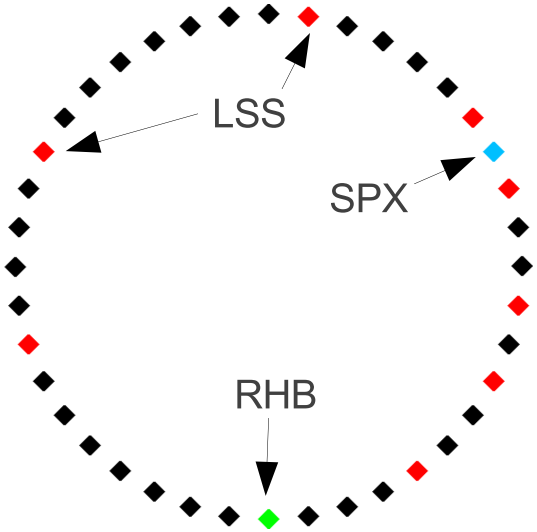
- Increases space available for ID from 4.8 to 7.7m
- Most cost-effective option for LSS
  - Still, hard to afford more than 8

A Few LSS Options for APS

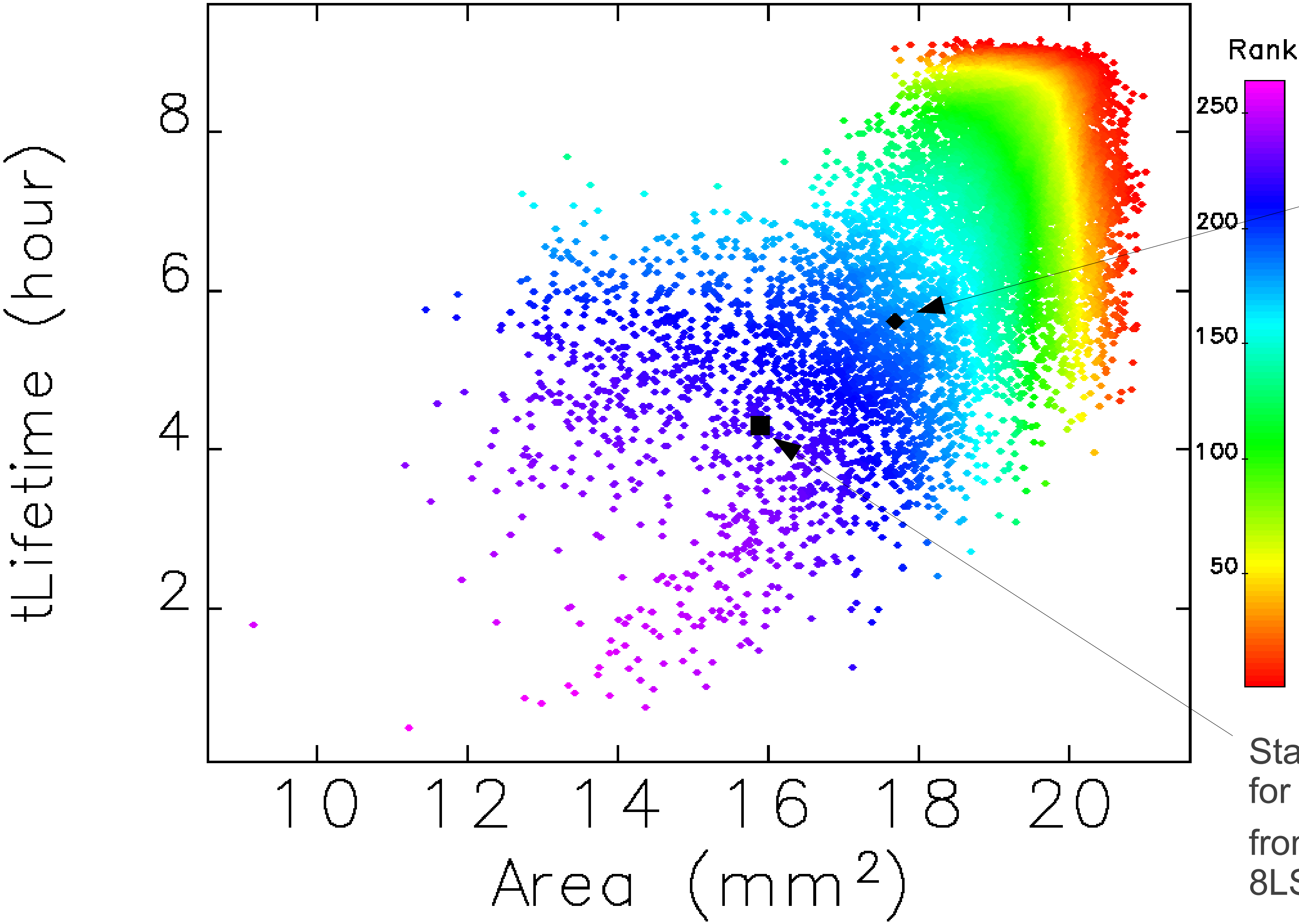


Lattice Considerations

- Traditionally, only symmetric arrangements considered viable
  - Easier to obtain large injection aperture and lifetime
  - Doesn't make users very happy
- New optimization methods indicate that non-symmetric arrangements should work
  - Apply parallel evolutionary algorithm to optimize injection aperture and lifetime in simulation
  - Use dozens of independent sextupole knobs
  - APS and ANL computing resources (Fusion, Intrepid) have made a significant contribution to progress
- Have developed three basic lattices:
  - 8 “random” LSS
  - 8RLSS + SPX in sector 7
  - 8RLSS+SPX + RHB in sector 19



Optimization of 8RLSS for $\xi_x = \xi_y = 7$



Started here from $\xi_x = \xi_y = 5$ optimization result.

Starting point for $\xi_x = \xi_y = 5$ from symmetric 8LSS sextupoles.

Ideal Beam Parameters for APS-U

Type	Rms Horizontal Size (microns)	Rms Horizontal Divergence (microrad)	Rms Vertical Size (microns)	Rms Vertical Divergence (microrad)
Today	275	11.3	8.5	3.0
APS-U: Short Straight	289	11.5	9.1	2.9
APS-U: Long Straight	302	11.3	11.9	2.2

Mockup Lattice Testing

- We can test LSS lattices using our independent power supplies
  - Turn off power supplies to mockup removing magnets
- V. Sajaev, L. Emery tested 8RLSS mockup lattice
  - Lattice has normal injection efficiency and lifetime
  - Was essential to steer the beam to the center of the sextupoles
  - Implication: cannot have significant steering of beam to compensate for misaligned beamlines
- V. Sajaev, A. Xiao tested 8RLSS+SPX+RHB mockup lattice
  - Lattice has normal injection efficiency
  - Lifetime is significantly reduced (5 hours at 100 mA)
  - Study of this lattice continues

Summary

- Electron beam is nominally gaussian in 6d
  - Beam can be described by 6d correlation matrix
  - Simplifications are possible but may be misleading
  - In real machine
    - Beam sizes, divergences vary between straights
    - Waist may not be at the center of the straights
    - Beam may be tilted
  - Would hope to improve some of this in the upgrade
    - At least provide more detailed information
  - Suggest that beamline design should consider how to reduce sensitivity to likely errors
- Upgrade lattice is under development
  - 8 “random” long straights
  - SPX and RHB insertions
  - Mockup lattices look workable